NISTIR 6030

THIRTEENTH MEETING OF THE UJNR PANEL ON FIRE RESEARCH AND SAFETY, MARCH 13-20, 1996

VOLUME 1

Kellie Ann Beall, Editor

June 1997
Building and Fire Research Laboratory
National Institute of Standards and Technology
Gaithersburg, MD 20899

U.S. Department of Commerce
William M. Daley, *Secretary*
Technology Administration
Gary R. Bachula, *Acting Under Secretary for Technology*
National Institute of Standards and Technology
Robert E. Hebner, *Acting Director*

A Universal Orifice Flow Formula

Howard W. Emmons - Professor Emeritus
Harvard University
317 Pierce Hall - Cambridge Ma 02138 - USA

Flow metering nozzles and orifices have been studied for a century and with adequate care in installation can measure flow rates to better than one percent. The growing demands of fire science has introduced new flow problems presented by doors and windows, burn through and other holes in the ceiling and fireman opened holes in the roof, horizontal or inclined. This paper presents a unified formula for all these cases. As usual, a practical ideal formula is theoretically derived and then empirical constants are added to correct for omitted phenomena. High precision is neither needed nor attainable since the nature of the vent (size , shape, edge geometry) is poorly known or not known at all. In addition the gas velocities and temperatures on the two sides of the vents are poorly or completely unknown. Finally experimental data for validation of flow coefficients are very limited or are as yet unavailable.

Introduction

It has become conventional to define an ideal flow through a nozzle or orifice by the equation 1 derived by use of Bernoulli's equation.

$$m = A(2\rho_f\Delta p)^{1/2} \qquad 1$$

This equation ignores various inlet and other flow effects and viscous boundary layers. For metering purposes , the Reynolds number is usually 10^4 or higher so equation 1 is corrected as in equation 2 by a flow coefficient

$$m = \overline{C}_D A(2\rho_f\Delta p)^{1/2} \qquad 2$$

where $\overline{C}_D \approx .98$ for a nozzle $\overline{C}_D \approx .6$ for an orifice. Figure 1. shows more detailed accuracy in the region Re $> 10^4$ (1). The low orifice coefficient .6 is caused by the contraction of the exit stream to a vena contracta area of $A_{vc} \approx .6A$.

When this same ideal flow equation 1 is used to compute the fire flow through an orifice in a horizontal surface (2,3,6), the flow coefficients are in the range .1 to .2. Without any apparent concern for how the coefficients got so low, the experimental results, including a region near $\Delta p = 0$ where simultaneous in-out flow occurs, are presented assuming the buoyancy caused by density difference requires a Froude Number for data presentation. Cooper (6) in particular has made an extensive empirical analysis assuming that

$$\overline{C}_D = \overline{C}_D(\overline{Fr}, \overline{Gr}, \Delta\rho/\rho, \Pi) \qquad \text{(Note: } \Pi \neq \pi \text{ see notation)} \qquad 3$$

Analysis

Consider the horizontal vent fire case of hot gas below and cold gas above. I will set it up with all my initial misconceptions to be corrected later. The positive direction is up. The pressure drop is defined as $\Delta p = p_i - p_o$ (negative if flow is down)

The density change is $\Delta\rho = \rho_o - \rho_i$ (negative if cold gas is below)

h = the distance up to the vena contracta (negative if down)

g' = the component of gravity inward perpendicular to the vent surface.

The flow controlling velocity is at the vena contracta and is given by Bernoulli as

$$v = (2\{\Delta p + \Delta\rho g'h\}/\rho_f)^{1/2} \qquad 4$$

the volume flow and mass flow follow as

$$Q = vA_{vc} \quad \text{and} \quad m = \rho_f Q = \rho_f v A_{vc} \qquad 5$$

To make these relations correct for all flow directions, pressures, and temperatures we need to insert all the correct signs and add flow coefficients for the omitted effects.

$$v = \text{sign}(\Delta p + \Delta\rho g'h)C_\mu(\text{sign}(h)2\{\Delta p + \Delta\rho g'h\}/\rho_f)^{1/2} \qquad 6$$

$$Q = \text{sign}(\Delta p + \Delta\rho g'h)C_\mu C_{vc}A(\text{sign}(h)2\{\Delta p + \Delta\rho g'h\}/\rho_f)^{1/2} \qquad 7$$

$$m = \text{sign}(\Delta p + \Delta\rho g'h)C_\mu C_{vc}A(\text{sign}(h)2\rho_f\{\Delta p + \Delta\rho g'h\})^{1/2} \qquad 8$$

where C_μ - corrects for viscous and other neglected flow effects

$C_{vc} = A_{vc}/A$ corrects for the flow area change to the vena contracta.

h - corrects for buoyancy effects from orifice to vena contracta

the flow coefficient $C_D = C_\mu C_{vc}$

For high Reynolds numbers (above 10^4) the buoyancy effects are unimportant but by crude observation $h \approx D$.

Consider the metering nozzle and orifice. The nozzle coefficient, C_D, Figure 1, Re > 10^4, is required to correct for viscous boundary layers and turbulence. Thus for the metering nozzle $C_D = C\mu$ (C_{vc}= 1). There is no nozzle vena contracta. The orifice coefficient has a viscous effect similar to the nozzle but also has a large dynamic contraction to the vena contracta controlling the flow area. thus for the orifice its flow coefficient $C_D = C_\mu C_{vc}$. Since C_D (orifice) $\approx .6$ and $C_\mu \approx .98$, $C_{vc} \approx .612$. 9

Note that below Re $\approx 10^4$ the nozzle flow coefficient falls while the orifice flow coefficient rises. Clearly viscous effects are increasing in importance relative to the dynamics as Re falls while for an orifice the falling dynamics also prevents the approach fluid from jumping off the orifice lip so vigorously and hence the vena contracta area becomes larger. As the Reynolds number falls C_{vc} is expected to continue to rise toward 1. The dashed line of figure 1 shows the computed C_{vc} by equation 9 for Re > 10^4 while the C_{vc} for Re < 10^4 is the expected effect (no data available). (much new test data is needed for Re < 10^4).

The Horizontal Orifice

The flow is given by equation 8. Figure 2 shows the predicted flows for various cases. For m > 0 the flow is up while for m < 0 the flow is down. If $\Delta\rho > 0$ (the fire case) and the flow is up h > 0, the flow varies with Δp as in figure 2a. Note that at $\Delta p = 0$ there is still upward flow by buoyancy.

$m_u = C_\mu C_{vc}(2\rho_d \Delta\rho g'h)^{1/2}$ and $m = 0$ at $\Delta p = -\Delta\rho g'h>0$ (no up flow. therefor flooding down flow) 10

If $\Delta\rho > 0$ and $h < 0$ the flow is down and at $\Delta p = 0$ there is still down flow by buoyancy

$m_d = -C_\mu C_{vc}(-2\rho_u \Delta\rho g'h)^{1/2}$ and $m = 0$ at $\Delta p = -\Delta\rho g'h>0$ (no down flow.Therefor flooding up flow) 11

If $\Delta\rho < 0$ (high density below) the upward flow ($h > 0$) is zero at $\Delta p = -\Delta\rho g'h > 0$ 12

and downward flow ($h < 0$) is zero at $\Delta p = -\Delta\rho g'h < 0$ 13

This last case is shown in figure 2c where a stable region with no flow is predicted as is too be expected.

Finally if $\Delta\rho = 0$ i.e. no density difference, figure 2b shows the result.

Experimental data (3,4) presents flow coefficients, $\bar{C}_D$ defined by equation 2. For this new theory $C_D = C_\mu C_{vc}$ is defined by equation 8. Thus C_D and $\bar{C}_D$ are related by

$\bar{C}_D = C_D\{1 + \Delta\rho g'h/\Delta p\}^{1/2}$ 14

To make the conversion requires values of h. At the lazy flooding flow, the distance "h" to the vena contracta is nearly zero as seen in the shadowgraphs of reference 3. However at flooding $\Delta p = \Delta\rho g'h$ while experiments give

$h/D = \Delta p/\Delta\rho g'D \ / \ \Delta p/\Delta\rho g'h = \Delta p/\Delta\rho g'D$ 16

This has the experimental value of about 2. (Present data has considerable scatter and no apparent correlation.). Clearly h is not the distance to the vena contracta as first assumed, It is the distance over which buoyancy has an influence on the flow. Some experimental values as high as 6 are not believable. New experimental work is essential to find and correct current mistakes in experiment and theory.

Another important change is to use the conventional dimensional variables for a viscous, buoyant flow. Thus

$C_D = C_D(\mathrm{Re}, \mathrm{Fr})$ $\quad \mathrm{Re} = VD/\nu$, $\mathrm{Fr} = V/(g'd)^{1/2}$ 17

The available data is inadequate to use this relation correctly. Experiments should be made holding one independent variable constant while the other is varied. Such data has never been taken.

The best that can be done with available data is to plot the experimental C_D vs Re as in figure 1. The lower curve shows the data which falls at $5\times10^2 < \mathrm{Re} < 4\times10^3$. The curve between Re = 4×10^3 and 10^4 is drawn by eye but the data fits together remarkably well. Using equation 9 and C_{cv} and C_D from figure 1 permits the calculation of C_μ over the whole Reynolds number range. In figure 1 C_μ for Re between 4×10^3 and 10^4 derived as above fits remarkably well. New data in this range is needed.

Since C_D and $C\mu$ curves were drawn (with good fit) by a logarithmic french curve, they plot as straight lines on cartesian coordinate paper and hence are defined by linear equations as shown on figure 1. The C_{vc} curve has a more complex formula, quadratic in log Re.

It is now clear why the flow coefficients are so low for the normal range of horizontal orifice flow. The Reynolds number is so low that the flow is dominated by viscous forces.

The flood point would be expected to be controlled by the Froude Number. Figure 3 shows how the Froude number at flood varies with the density change $\Delta\rho/\rho$. (the data of Tan and Jaluria (3) is puzzling. Their experimental work appears very good. Either their flood data is bad or the other $Fr(\Delta\rho/\rho)$ data (2.5) is some how inadequate). If $\Delta\rho = 0$, the boundary between up and down flow is at $\Delta p = 0$ and hence $Fr = 0$ as plotted. The solid curved line is the best fit while the dashed straight line is accurate enough for fire purposes.

It remains to compute the up and down flow between the flood limits. At flood conditions, measurements (4) at $\Delta p = 0$ gave

$$Q_d/(gD^5\Delta\rho/\rho)^{1/2} = -.055 \qquad 18$$

from which follows the $\Delta p = 0$ downward mass flow

$$m_d/\Delta\rho A[gD]^{1/2} = -.202 \qquad 19$$

The up and down region is shown in figure 4. The two flood points are shown c which terminates the one way flow regions. There is too little data for the flow in this region, so a linear assumption is used. For up flow, for example, the flow is assumed to vary as the straight line from the upward flood point A to zero at the pressure drop (negative) of the downward flood point..

To find the flow (up or down) at any Δp in the two flow region, we note that at flood

$$Fr_f = V_f/(g'D)^{1/2} = m_f/\rho_f A(g'D)^{1/2} = .591\ \Delta\rho/\rho_f \qquad 20$$

so that

$$m_f/\text{sign}(h)\Delta\rho A(g'D)^{1/2} = .591 \qquad 21$$

The corresponding pressure drop is

$$\Delta p_f = \text{sign}(h)\ .0873\ \Delta\rho^2 g'D/C_D^2\rho_f \qquad 22$$

Note that unlike figure 2 (where it was assumed that $h_u = D$) the magnitude of the pressure drop for up and down flow flood are different because of $C_D^2\rho$ and therefore h by equation 16 is different for up and down flow. However the linear assumption for the conditions of the experiment of equation 18 (4) at Δp = 0 gives

$$m_d/\Delta\rho A(g'D)^{1/2} = -.275 \text{ compared to equation 19, } -.202 \qquad 23$$

While this agreement is not perfect, it is better than our general knowledge of the size and shape of a burn through hole in a ceiling. Much more experimental work is required to measure the actual up and down flows.

To compute the flow through a horizontal vent given the pressures and densities one must.

1. From the densities compute $\Delta\rho/\rho_f$
2. Compute the Froude number $Fr = .591\ \Delta\rho/\rho_f$
3. Compute the Reynolds number $Re = Fr(g'D^3)^{1/2}/v$
4. Look up C_D from figure 1 (or compute it from equations given there)
5. Compute m from equation 8
6. Compute m_f from equation 21. Two values + and -
7. If $|m| > |m_f|$ then m is the one way flow through the vent
8. If $|m| < |m_f|$ then there is two way flow through the vent
9. Compute Δp_f from equation 22 for both up and down flow. $\Delta p_f = \Delta p_u > 0$ up, $\Delta p_f = \Delta p_d < 0$ down
10. Compute $m_u = |m_f|(\Delta p-\Delta p_d)/(\Delta p_u-\Delta p_d)$ and $m_d = |m_f|(\Delta p-\Delta p_u)/(\Delta p_u-\Delta p_d)$

These are the up and down flows in the two flow region.

This theory like many others for flow through a horizontal vent contains many assumptions which can only be removed by careful experimentation.

The Vertical Vent

In this case the gravity component perpendicular to the vent surface is zero; $g' = 0$. Gravity acts parallel to the vent surface so that both inside and outside pressures decrease with height which must be found by integration.

$$\Delta p = \Delta p_o + \int_o^y \Delta\rho g dy \qquad 24$$

which for constant densities ρ_o and ρ_i becomes

$$\Delta p = \Delta p_o + \Delta\rho g y = \Delta p_s - \Delta\rho g(H - y) \qquad 25$$

If $\Delta\rho = 0$, the pressure drop Δp is the same at all levels. Since the pressure difference varies with height y, the equations 6,7,8 must be applied to an area element $dA = w\,dy$. Thus

$$v = \mathrm{sign}(\Delta p)C_\mu(\mathrm{sign}(h)2\Delta p/\rho)^{1/2} \qquad 26$$

$$dQ = \mathrm{sign}(\Delta p)C_\mu C_{vc} w dy(\mathrm{sign}(h)2\Delta p/\rho_f)^{1/2} \qquad 27$$

$$dm = \mathrm{sign}(\Delta p)C_\mu C_{vc} w dy(\mathrm{sign}(h)2\rho_f\Delta p)^{1/2} \qquad 28$$

These equations have included the customary assumption that the flow velocity at any level y depends upon the difference in pressure at the <u>same level</u> y far from the vent. This ignores the fact that buoyancy causes the in-out flow boundary in the vent to be somewhat higher (7). This omission must also be corrected by the flow coefficients. If the density is everywhere the same, the total mass flow is

$$m = \mathrm{sign}(\Delta p)C_\mu C_{vc} A(\mathrm{sign}(h)2\rho_f\Delta p)^{1/2} \qquad 29$$

Only in this case is zero flow possible (with $\Delta p = 0$)

If both ρ_o and ρ_i are constant at all levels but $\Delta\rho \neq 0$, integration then gives the one way flow as

$$m = \mathrm{sign}(\Delta)8^{1/2}/3C_\mu C_{vc} A\rho_f^{1/2}(\,|\Delta p_s| + (\Delta p_s\Delta p_o)^{1/2} + |\Delta p_o|\,)/(\,|\Delta p_s|^{1/2} + |\Delta p_o|^{1/2}) \qquad 30$$

If either or both densities vary with height, then the pressure difference varies with height and equations 26,27,28 must be integrated. However if the densities are constant in layers, equation 30 can be applied to each layer.

Again for constant densities, $\Delta\rho \neq 0$, the flooding flows occur for outflow at $\Delta p_o = 0$ and $\Delta\rho > 0$ or $\Delta p_s = 0$ and $\Delta\rho < 0$ while for inflow $\Delta p_o = 0$ and $\Delta\rho < 0$ or $\Delta p_s = 0$ and $\Delta\rho > 0$. As the pressure drop at the bottom of the vent goes from large positive to large negative, the out flow decreases from a large value to the flood value at $\Delta p_o = 0$. Then the boundary between the in and out flow moves from the bottom to the top of the vent. The inflow flooding flow occurs at $\Delta p_s = 0$ at which time $\Delta p_o = -\Delta\rho g H$. For all $\Delta p < -\Delta\rho g H$ there is inflow only.

Unlike the horizontal vent, there is no zero flow region in Δp and the in-out flow boundary is fixed at one (or more) heights depending on the specific case. For the horizontal case the in-out boundary wanders randomly over the vent area.

An extensive study has not yet been made of the available data. For most fire purposes a flow coefficient of .68 is sufficiently accurate over the whole Reynolds number range. However available data (7) (with considerable scatter) shows that for Re < 2000 that the outflow coefficient roughly follows C_μ and the inflow coefficients follow C_D. Also (by eye) (7) $h \approx D$.

The Inclined Vent

Figure 5 shows such a vent. If the pressure drop across the vent at the bottom is Δp_o, the pressure drop at any other height must be found by integration.

$$\Delta p = \Delta p_o + \int_0^y \Delta\rho g \sin\theta \, dy \qquad 31$$

which for constant densities gives

$$\Delta p = \Delta p_o + \Delta\rho g\, y \sin\theta = \Delta p_s - \Delta\rho g(H - y)\sin\theta \qquad 32$$

The equations 6,7,8 must again be applied at each y

$$v = \mathrm{sign}(\Delta p + \Delta\rho g\, h \cos^2\theta)C_\mu(\mathrm{sign}(h)2\{\Delta p + \Delta\rho g\, h\cos^2\theta / \rho_f)^{1/2} \qquad 33$$

$$dQ = \mathrm{sign}(\Delta p + \Delta\rho g\, h \cos^2\theta)C_\mu C_{vc} w\, dy\,(\mathrm{sign}(h)2\{\Delta p + \Delta\rho g\, h\cos^2\theta\} / \rho_f)^{1/2} \qquad 34$$

$$dm = \mathrm{sign}(\Delta p + \Delta\rho g\, h \cos^2\theta)C_\mu C_{vc} w\, dy\,(\mathrm{sign}(h)2\rho_f\{\Delta p + \Delta\rho g\, h\cos^2\theta\})^{1/2} \qquad 35$$

Again the flow can only be determined by integration of each specific case. There is no zero flow case since again $\Delta p_o = 0$ and Δp_f are the two flooding limits for ρ_o and ρ constant ($\Delta\rho \neq 0$). The transition from in to out flow occurs by the zero flow location in the vent moving from y = 0 to y = H. Finally the flow with uniform but different densities is given by equation 30 where the pressure variables are replaced by

$$\Delta p \to \Delta p + \Delta\rho g\, h\cos^2\theta : \quad \Delta p_o \to \Delta p_o + \Delta\rho g\, h\cos^2\theta : \quad \Delta p_s \to \Delta p_s + \Delta\rho g\, h\cos^2\theta \qquad 36$$

As the inclination θ approaches zero, the zero flow location which has started at the bottom and moved to the top loses its significance since Δp_f flood is forced by buoyancy before $\Delta p_o = 0$ at the bottom. Therefore as $\theta \Rightarrow 0$ the in-out flow locations wander randomly over the vent area, tripped by vent edge irregularities and inlet flow disturbances. If θ becomes so small that either or both Δp_o or Δp_s fall between the two flood values Δp_f, the flow will become that of a horizontal vent.

Conclusion

The flow through fire vents (often ill defined) can be computed for all vent shapes and orientations. The accuracy is the highest attainable with the present meager data from which to compute the effective flow coefficients C_D and buoyancy effective lengths h. Many more experimental studies are necessary to get the desired accuracy. In fact the accuracy of flow through burn through holes in walls or ceilings may be forever impossible because of the probable impossibility of ever predicting the size and shape of the vent.

There are obviously enough challenging fire problems to occupy a generation of Ed Zukoskis

Nomenclature

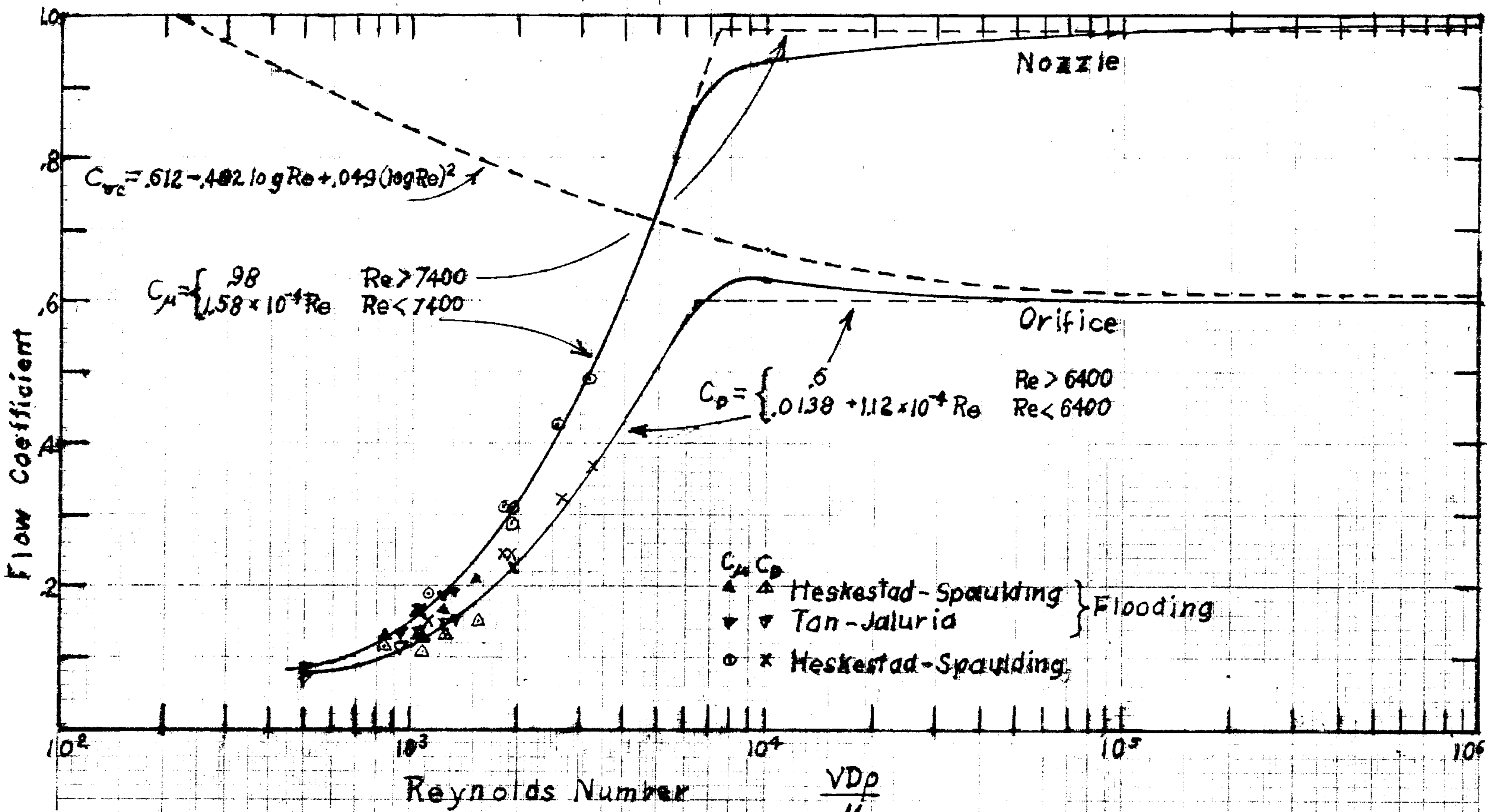
A	vent area
A_{cv}	vena contracta area
C_D	new theory flow coefficient
C_D	old theory flow coefficient
$C_{vc} = A_{vc}/A$	contraction factor
C_μ	viscous correction factor
D	vent diameter
$Fr = V/(g'D)^{1/2}$	Froude Number
$Fr = v/(g'D\Delta\rho/\rho)^{1/2}$	
Gr	Grashoff number
g'	component of g normal to vent
g	gravity constant
h	effective buoyancy length
H	height of rectangular vent
m	Mass flow
p	Pressure
$Re = VD\rho/\mu$	Reynolds number
v	vena contracta velocity
$V = m/\rho_f A$	Velocity in the vent
w	width of rectangular vent
y	coordinate across vent

Greek Letters and Subscripts

$\Pi = \Delta p/4g\Delta\rho D$	
θ	roof inclination
ρ	density
ρ	mean density
$_d$	lower variable
$_f$	density of flowing fluid or flood
$_i$	inside variable
$_o$	outside or bottom variable
$_s$	soffit variable
$_{vc}$	vena contracta variable
$_u$	upper variable

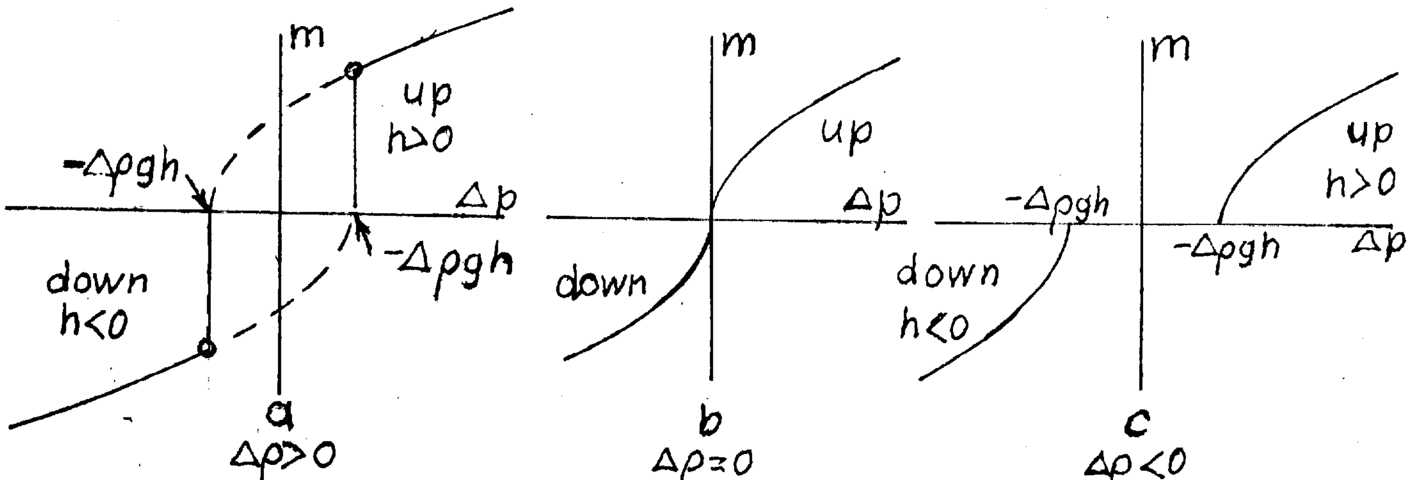
References

1. Marks L.S. Mechanical Engineers Handbook 5th edition 1951
2. Heskestad G. and Spaulding R.D. Inflow of Air Required at Wall and Ceiling Apertures to Prevent Escape of Fire Smoke Proc. 3rd Simp. Fire Safety Sci. p 919-928, 1991
3. Tan Q. and Jaluria J. Flow Through Horizontal Vents as Related to Compartment Fire Environments. NIST-GCR-92-604 p 1-89, 1992
4. Epstein M. Buoyancy-Driven Exchange Flow Through Small Openings in Horizontal Partitions. J. Heat Transfer 110 p885-893 1988
5. Epstein M. and Kenton M. Combined Natural Convection and Forced Flow Through Small Openings in a Horizontal Partition, with Special Reference to Flows in Multicomponent Enclosures. J Heat Transfer 1989 p980-987 1989
6. Cooper L. Combined Buoyancy and Pressure- Driven Flow Through a Horizontal Vent NISTIR 5384 p1-43 1994
7. Prahl J. and Emmons H, Fire Induced Flow Through an Opening Comb. and Flame 25 p369-385 1975.



Flow Coeficients for Nozzles and Orificies

Figure 1



Effect of $\Delta\rho$ on Flow Through Horizontal Vent
Figure 2

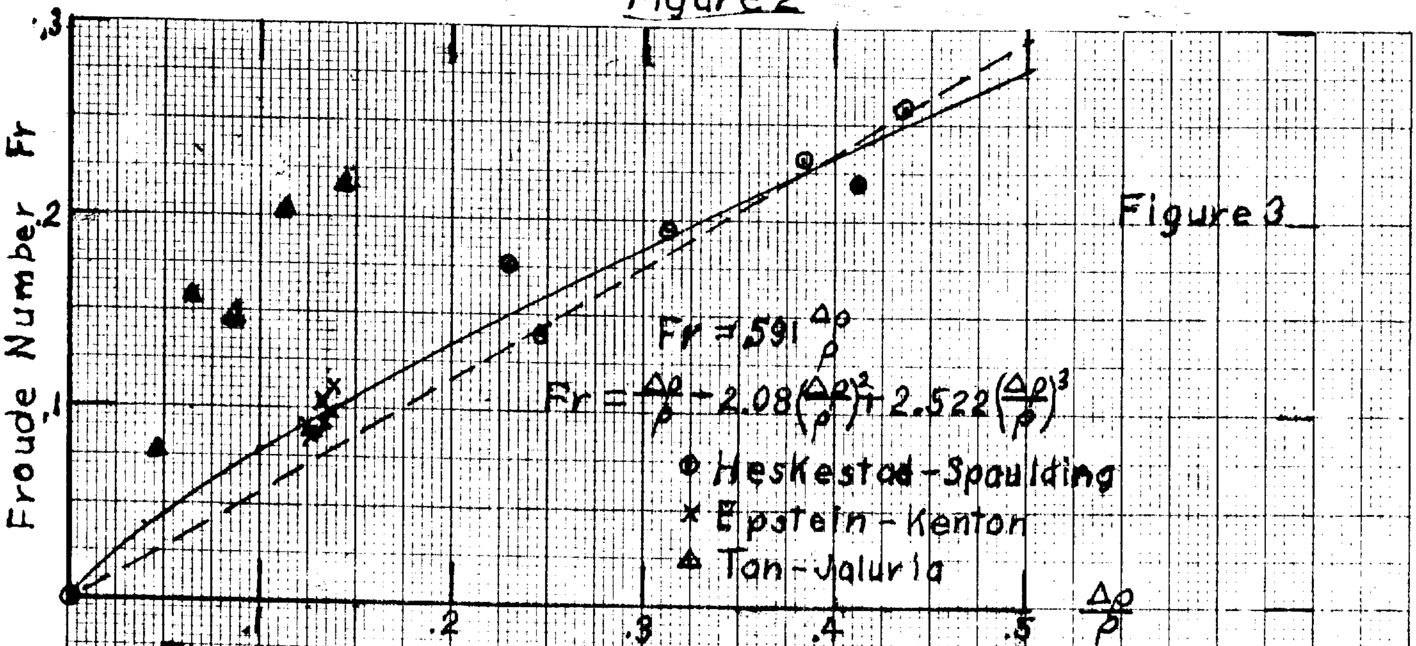
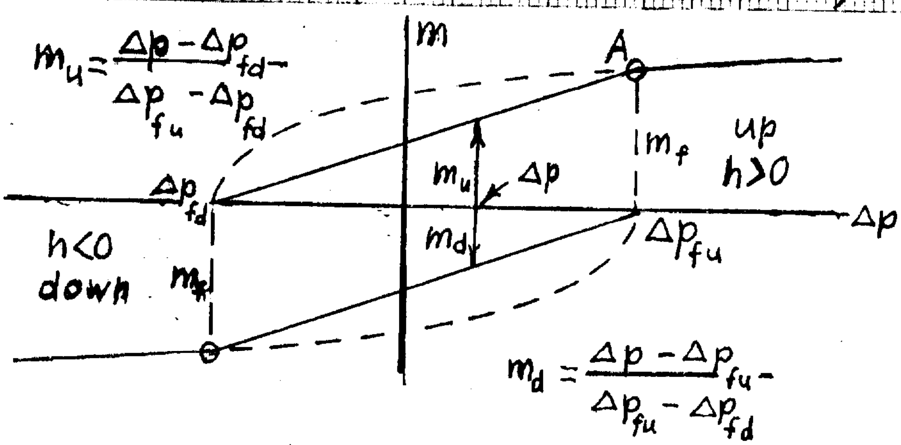


Figure 3

Flood Froude Number as Controled by Density Differance



Two Flow Region Figure 4

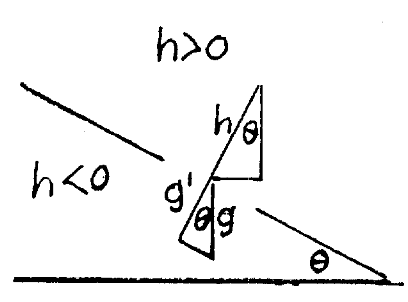


Figure 5
Inclined Vent

Discussion

Henri Mitler: Does this work of yours include the possibility of the periodic motion like when we fill up a bottle with water and then turn it upside down, it goes glug, glug, glug?

Howard Emmons: I have no data to answer that question. I suspect that the corrections are not very significant, but I don't really know. On the other hand, this has not been considered directly and does involve additional effects. In order to have oscillator flow, you have to have a capacity for absorbing extra mass and not oil. So there has to be an influence by the oscillating flow on the fire or something or other to permit that oscillation, that has not been included here at all.

Edward Zukoski: We have tried to do some of these experiments near the flooding point and found that it was the other effects that you talked about, that is how you contain the upper volume and so forth, that were very important in fixing the frequencies and so forth of the glug, glug, glug.

Gunnar Heskestad: Howard, when you presented your data, you presented it as a function of Reynolds number, but the data involved Froude numbers as well. I wanted to know how you decided to just present it as a function of Reynolds number.

Howard Emmons: The decision was fairly simple and elementary. The primary reason was because I tried it with Reynolds number alone and it worked beautifully, which said to me that my correction for buoyancy worked. The flow coefficients that I used in that correlation had to be recomputed based upon my formula. I could not use the one that you and others could correctly use.

Leonard Cooper: We've looked at the fire situation as unstable, heavy fluid or light fluid and you have a general solution which is a different approach. The solutions that we looked at are good and correlate well with data there for high Grashof number data. This idea is also confused with the fact that Heskestad data contains some Grashof number data which also does not correlate. In this sense, Grashof number does play a role and one has to be careful, it would appear.

Howard Emmons:
It is entirely possible that the Grashof number is the number that has to be added, as I mentioned earlier, in order to get a better correlation.